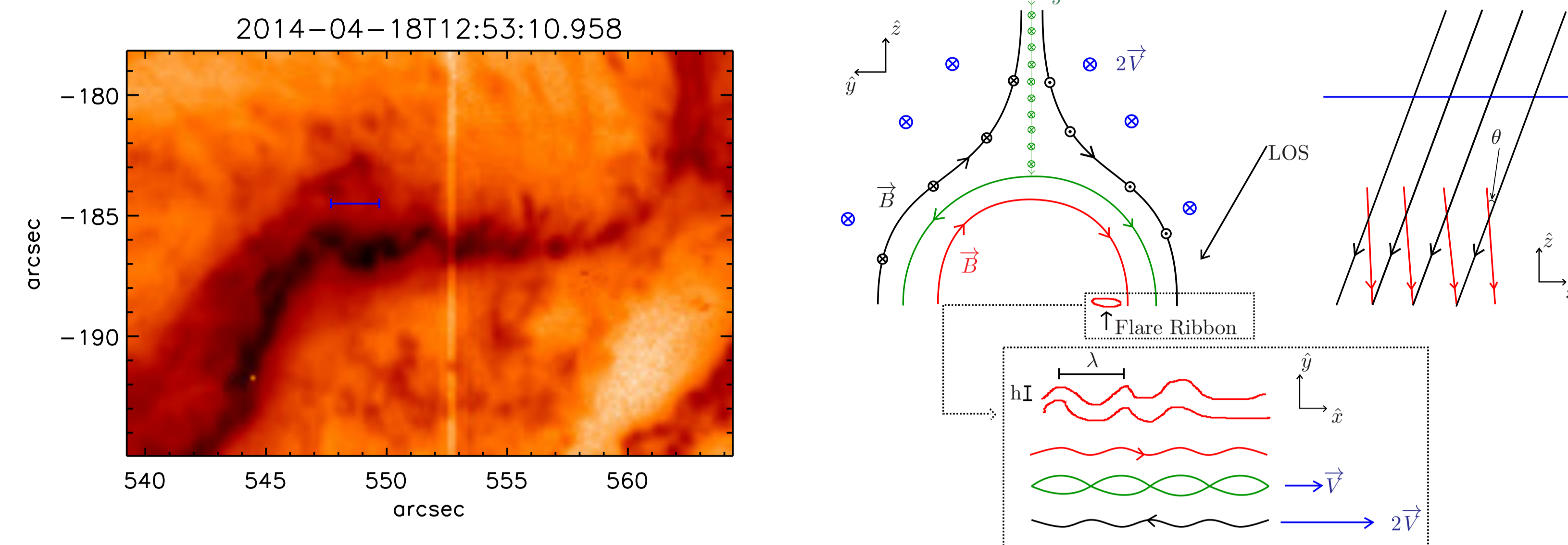


Abstract

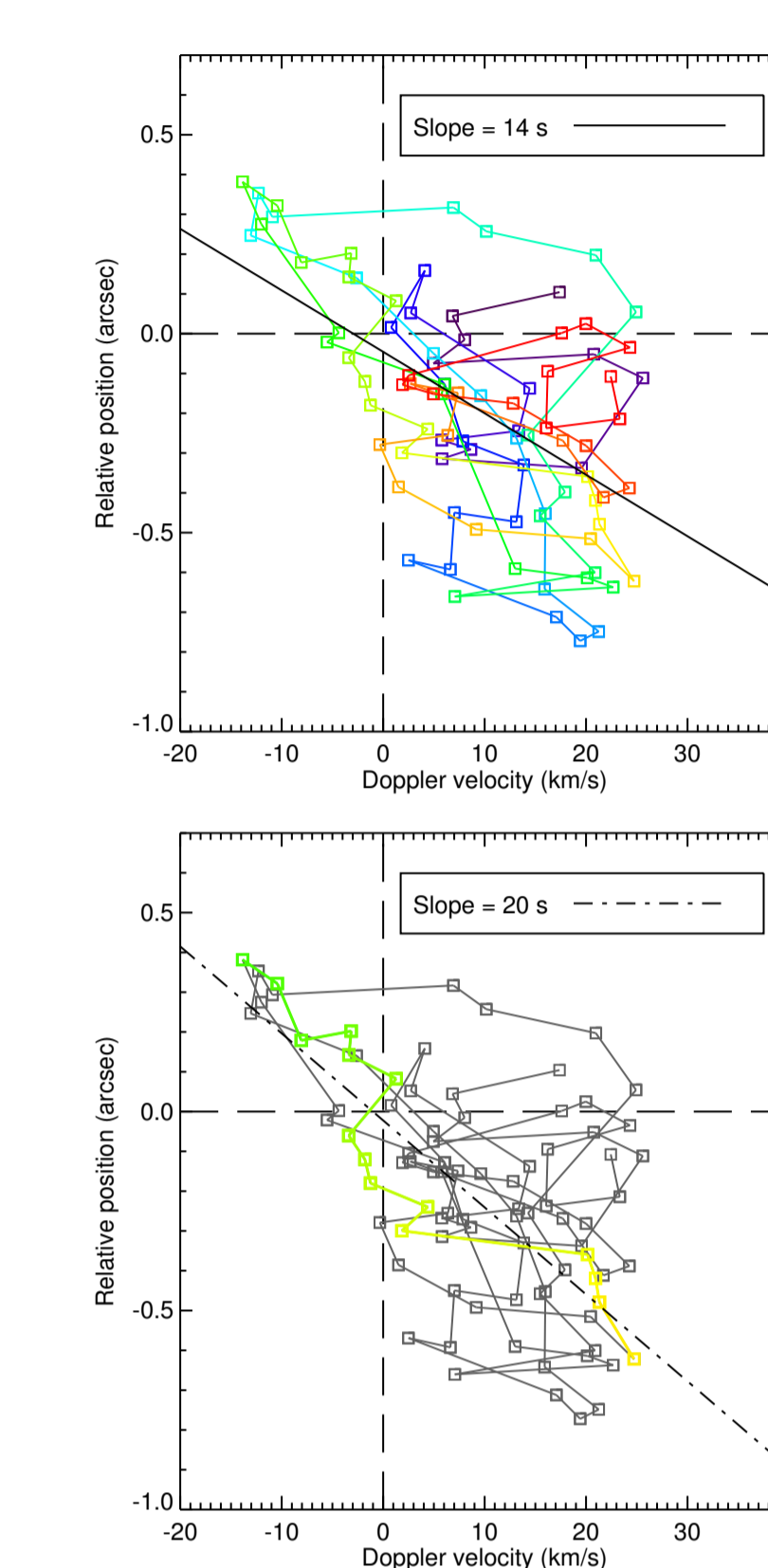
On April 18, 2014 (SOL2014-04-18T13:03) an M-class flare was observed by IRIS. The associated flare ribbon contained a quasi-periodic sawtooth pattern that was observed to propagate along the ribbon, perpendicular to the IRIS spectral slit, with a phase velocity of $\sim 15 \text{ km s}^{-1}$ [1]. This motion resulted in periodicities in both intensity and Doppler velocity along the slit. These periodicities were reported by Brannon et al. [1] to be approximately $\pm .5$ arcseconds in position and $\pm 20 \text{ km s}^{-1}$ in velocity and were measured to be $\sim 180^\circ$ out of phase with one another. This quasi-periodic behavior has been attributed by others to bursty or patchy reconnection [2, 3] and slipping occurring during three-dimensional magnetic reconnection [5, 4]. While able to account for periodicities in both intensity and Doppler velocity these suggestions do not explicitly account for the phase velocity of the entire sawtooth structure, or for the relative phasing of the oscillations. Here we propose that the observations can be explained by a tearing mode instability occurring at a current sheet across which there is also a velocity shear. We suggest a geometry and local plasma parameters for the April 18 flare which would support our hypothesis. Under this proposal the IRIS observations of this flare may provide the most compelling evidence to date of a tearing mode occurring in the solar magnetic field.

Sawtooth Flare Ribbon and Proposed Magnetic Field Configuration



The IRIS 1400 Å Slit Jaw image (left) shows the sawtooth flare ribbon (dark) and its orientation to the IRIS slit (light line) in an inverse log scale. The ribbon was observed to propagate to the right at $\approx 15 \text{ km s}^{-1}$. We propose (right cartoon) that during the flare, overlying magnetic field lines (black) are deflected by a small angle while the recently reconnected inner field lines (red) remain undeflected. This creates a secondary current sheet along the separatrix. The velocity of the open field, causing the deflection, creates an asymmetric shear flow across the secondary current sheet. This causes TM islands (green) to propagate along the sheet which cyclically perturbs surrounding plasma and therefore the flare ribbon (red squiggles). Each panel of the cartoon shows a different view of the configuration, indicated by coordinate arrows.

Observed Oscillations



This figure reproduced with permission from Brannon et al. [1] shows an oscillation of $\approx \pm 20 \text{ km s}^{-1}$ in Doppler velocity and $\approx \pm 0.5''$ in slit position that are $\sim 180^\circ$ out of phase. The color scale indicates time in seconds. The top panel shows the full measurement and the bottom panel shows the clearest of the oscillations.

Tearing Mode with Velocity Shear

We numerically solve [6, 7] for the fastest growing eigenmode of the dimensionless Tearing Mode Equations with Velocity Shear, Equations 1 and 2 with linear operator \mathcal{L} and initial fields F and G .

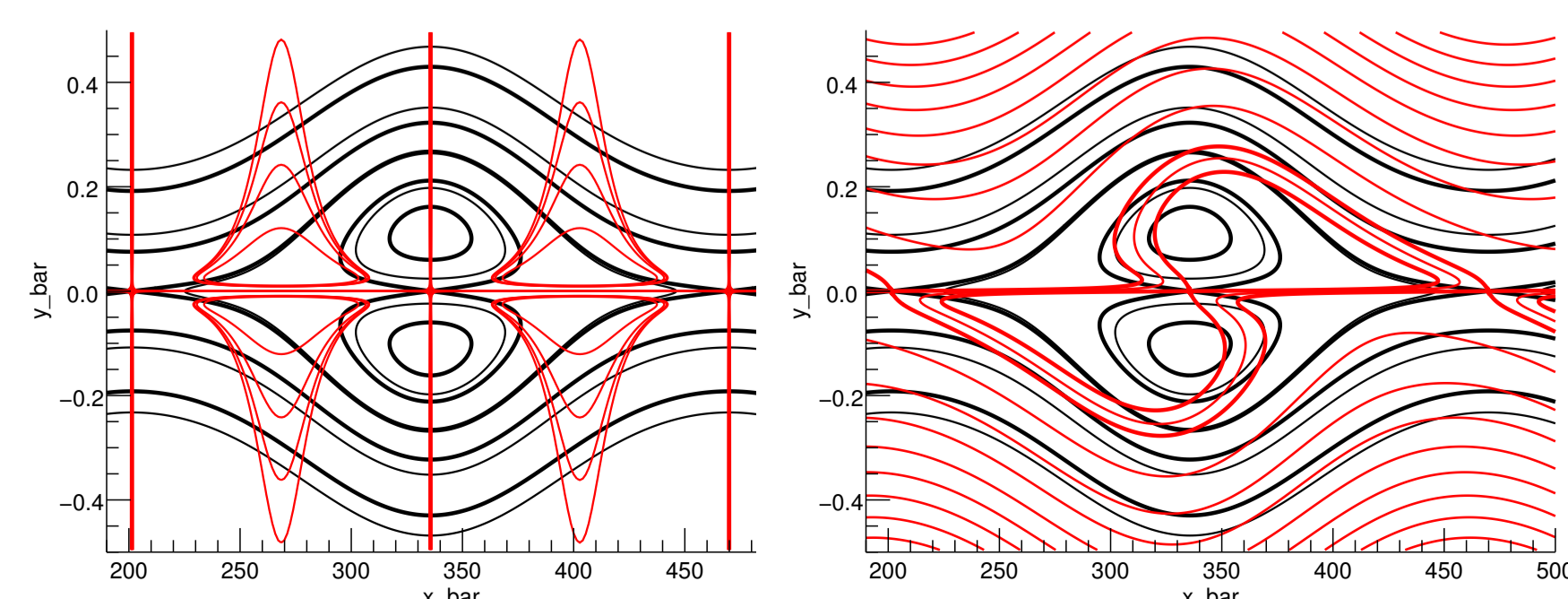
$$\frac{\partial \bar{B}}{\partial \bar{t}} = i\bar{k}(F\bar{u} - G\bar{B}) + S^{-1}\mathcal{L}\bar{B}, \quad (1)$$

$$\frac{\partial \bar{u}}{\partial \bar{t}} = i\bar{k}\{F\bar{B} - G\bar{u} + \mathcal{L}^{-1}(G''\bar{u} - F''\bar{B})\}, \quad (2)$$

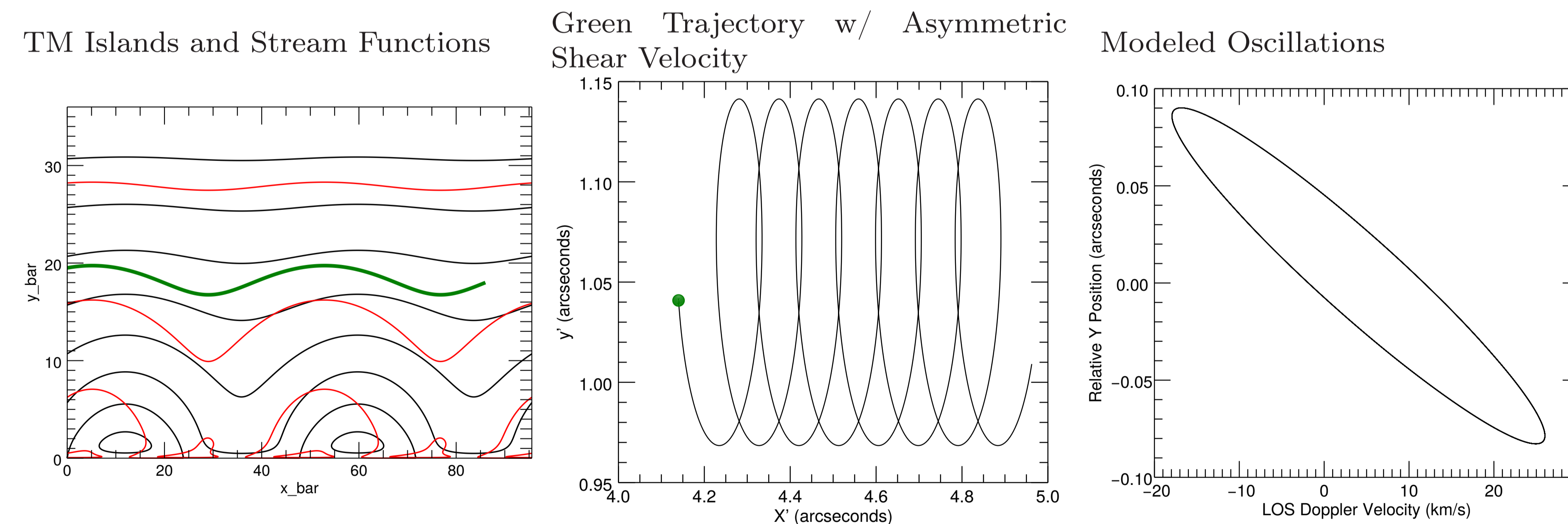
$$\mathcal{L} = \frac{\partial^2}{\partial \bar{y}^2} - \bar{k}^2, \quad (3)$$

$$F(\bar{y}) = \frac{B_{0x}}{B_0} = \tanh(\bar{y}), \quad G(\bar{y}) = \frac{u_{0x}}{v_a} = \bar{V} \tanh(\bar{y}), \quad (4)$$

Contours of dimensionless magnetic field, \bar{B} (black), and velocity, \bar{u} (red), with shear flow $V = 0$ and $0.1 v_a$ are shown below. These eigenmodes have dimensionless wavenumber, $\bar{k} = .0234$, and Lundquist Number, $S = 1 \times 10^7$.



Modeled Oscillations



Red and green curves (left) show trajectories of fluid elements when viewed in a frame where the TM islands (black) are stationary and the shear flow is symmetric. Elements away from the CS (e.g. green curve) move mostly leftward with a velocity approaching the far-field value. The center panel shows the trajectory of the green element viewed in a frame where the shear vanishes far upward and the islands move rightward. The oscillations in both slit-position and line-of-sight Doppler velocity, of the center trajectory, are plotted in the right panel. This panel takes into account the position of the flare ribbon on the solar disk and can be directly compared to the oscillations observed by Brannon et al. [1] in the upper right of the poster.

Conclusion

Our linear model of the Tearing Mode instability with velocity shear reproduces observed flare ribbon oscillations to satisfactory accuracy. We believe that a non-linear model would only better describe the observations and confirm that this is indeed a compelling and quantitative measurement of a Tearing Mode instability on the sun.

Acknowledgment

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References

- [1] Brannon, S. R., Longcope, D. W., & Qiu, J. 2015, ApJ, 810, 4
- [2] Brosius, J. W., & Daw, A. N. 2015, ApJ, 810, 45
- [3] Brosius, J. W., Daw, A. N., & Inglis, A. R. 2016, ApJ, 830, 101
- [4] Li, T., Yang, K., Hou, Y., & Zhang, J. 2016, The Astrophysical Journal, 830, 152
- [5] Li, T., & Zhang, J. 2015, ApJ, 804, L8
- [6] Ofman, L., Chen, X. L., Morrison, P. J., & Steinolfson, R. S. 1991, Physics of Fluids B, 3, 1364
- [7] Steinolfson, R. S., & van Hoven, G. 1983, Phys. Fluids, 26, 117